LBNL QuarkNet Lecture / July 25, 13 700 002 003 ABB

What we can learn about our universe using the

Cosmic Microwave Background Radiation

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Goals for today

- What the CMB is
- How we measure it
- What it can tell us about the universe.

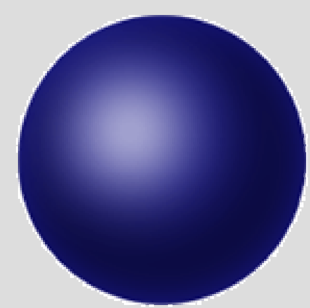
From our perspective as optical observers, the universe is a rich place full of structure, detail and beauty.

What is cosmology?

- Step back to larger scales, and the universe that surrounds us is extremely uniform-
- on large (Cosmological) scales, the universe is
  - homogenous (the same everywhere)
  - isotrophic (looks the same in every direction)
- Loosely put, ***cosmology is the study of our universe on these scales.***

This infinite cylinder is a 2d homogeneous surface, but it is not isotrophic.

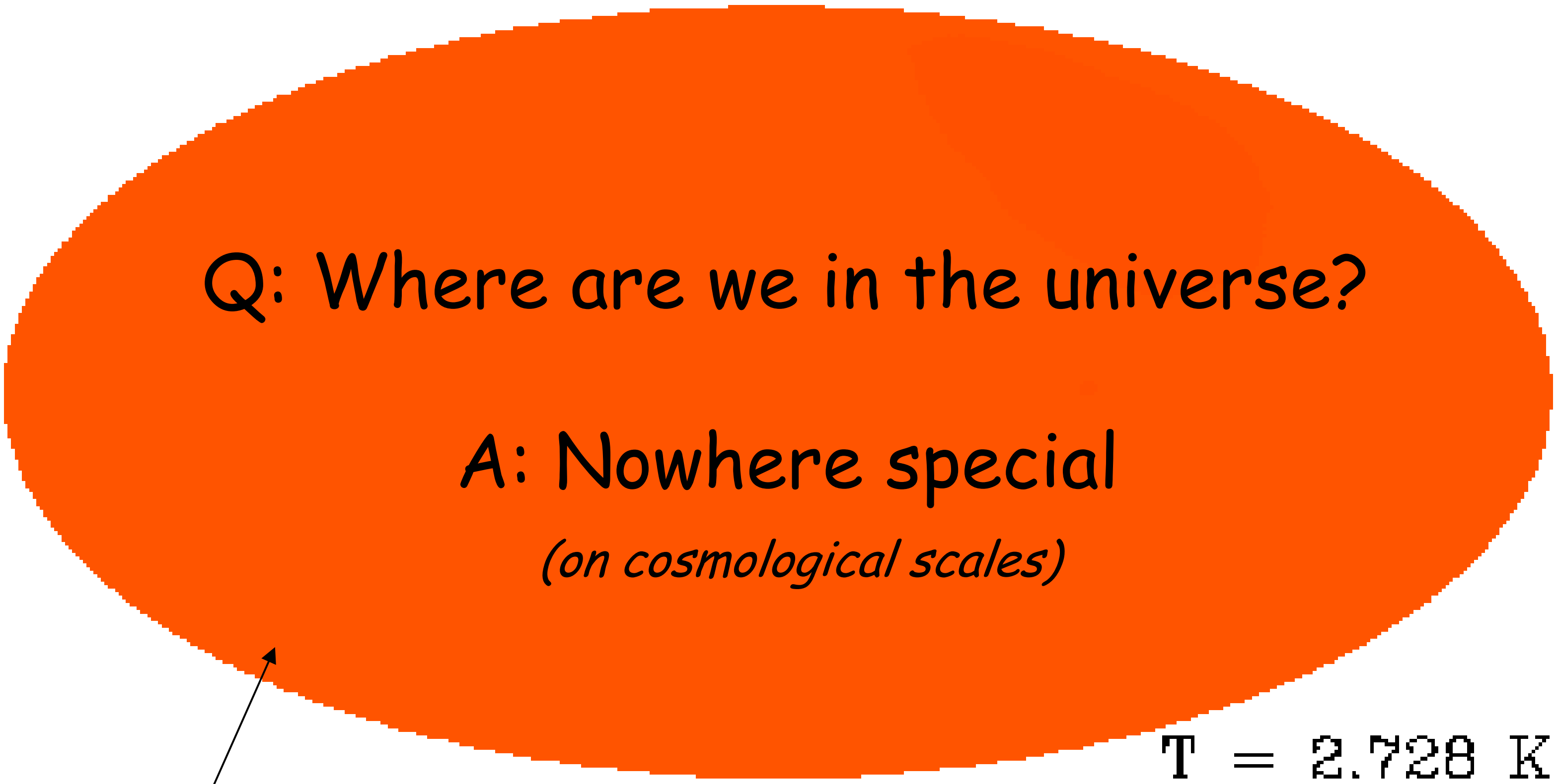
The 2d surface of this sphere is isotrophic, and therefore also homogeneous.



Q: Where are we in the universe?

A: Nowhere special

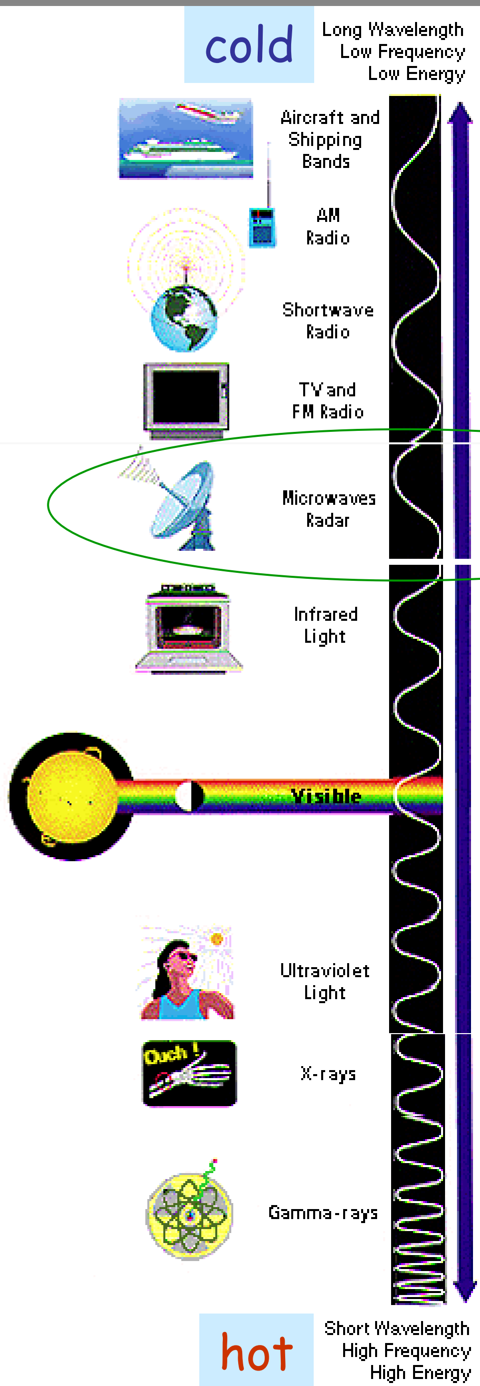
(on cosmological scales)



"Photograph" of the universe in the Microwave band.
Real Experimental DATA from the COBE satellite, 1992.

EM Spectrum

The Electromagnetic Spectrum



cm→km
10^{-2}–10^{3} m

mm→cm
10^{-3}–10^{-2} m

μm
10^{-6}–10^{-4} m

100s nm
10^{-7}–10^{-6} m

1–10^{2} eV

10^{2}–10^{5} eV

$>10^{5}$ eV

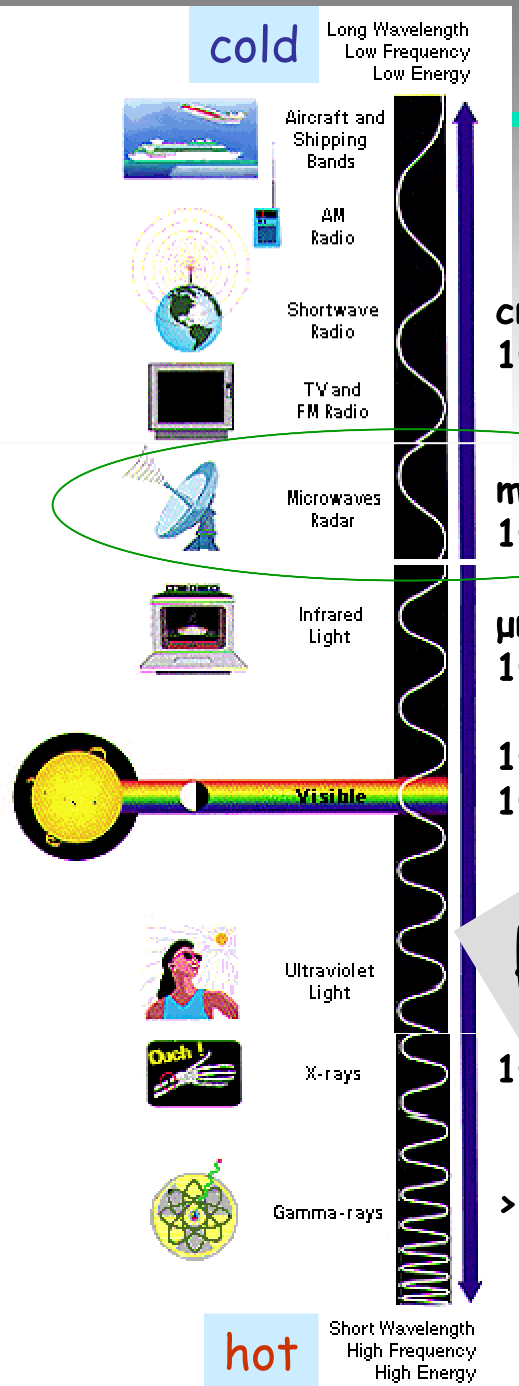
different information is encoded in different bands.

- radiowaves: i.e. radar

← CMB Photons now.

- visible: this is how we see the world around us.
- x-rays: i.e. dentist/doctor.
- gamma-rays: highest energy particles we know of…

The Electromagnetic Spectrum



cm→km
10^{-2}–10^{3} m

"CMB" photons in the future.

mm→cm
10^{-3}–10^{-2} m

CMB

µm
10^{-6}–10^{-4} m

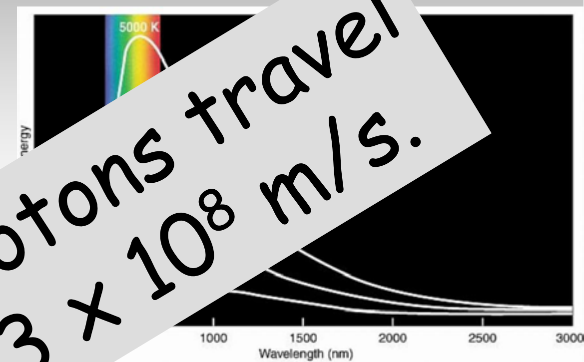
100s nm
10^{-7}–10^{-6}

10 eV

$>10^{5}$ eV

"CMB" photons a long time ago.

All these "different" photons travel at the same speed, $c = 3 \times 10^{8}$ m/s.

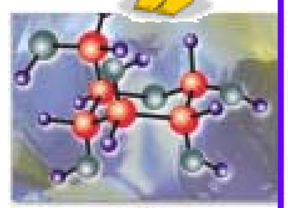
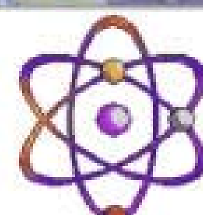
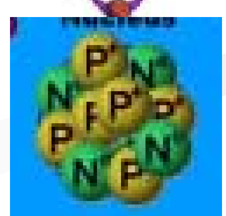


The Horizon

- light – and indeed any information – cannot be transmitted faster than the *speed of light, c*.
- For a universe that is L=13.7 billion years old, information could be exchanged over a maximum distance Lc.
- This defines "*our horizon*".
- As time moves forward, our horizon increases!.
- *The Horizon problem*: we see structures (e.g. the universe!!) that are uniform on super-horizon scales.

- Since light coming from further away takes longer to get here, the objects that emit the light are from an earlier time, because the light was emitted a long time ago.

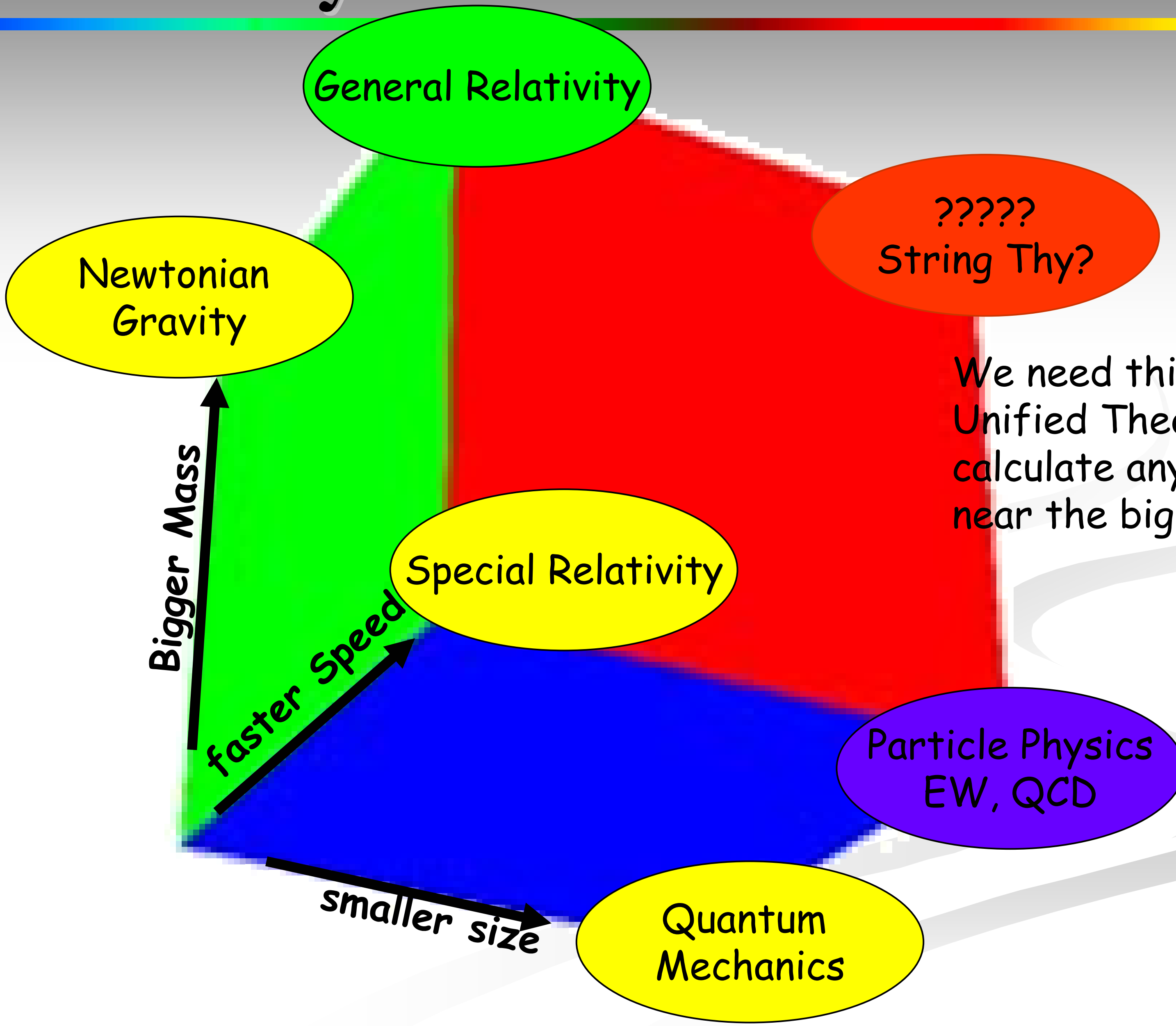
observations of distant objects are observations of our universe at a younger age.

Size (m)	Object		Force	Expert
10^{21}	>= Galaxies		Gravity	Cosmologists
10^{6}	Stars & planets			Astronomers
1	Living Things		Instinct Romance Biology	Psychologists Taxi Drivers Biologists
10^{-9}	Molecules		Electromagnetism	Chemists Pharmacists
10^{-10}	Atoms			
10^{-15}	Neutrons/protons		Weak Force Strong Nuclear Force	Nuclear & Particle Physicists

Thanks to A. De Rujula for this slide idea.

on different length scales, different forces are relevant– and so we use different theories and equations.

Physics Theories



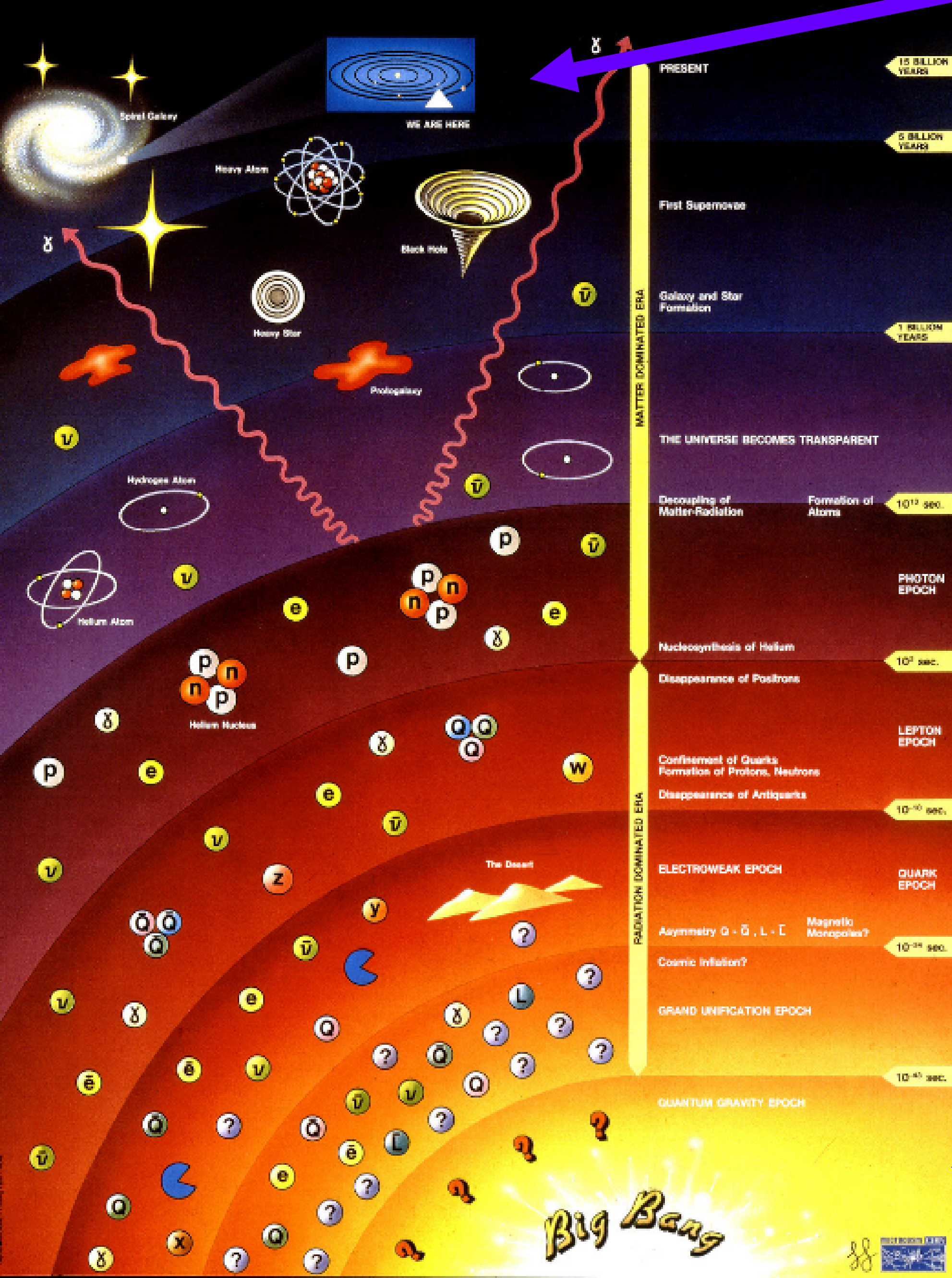
We need this Grand Unified Theory to calculate anything near the big bang!

The History of the Universe

Act I: a photon's journey from the opposite ends of time.

History of the universe

You are here



NOW (13.7 Billion years)

Large Scale Structure
Stars form (1 Billion years)

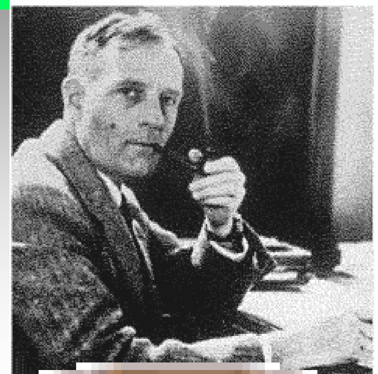
Surface of Last Scattering
Atoms Form (300 000 years)
CMB Produced

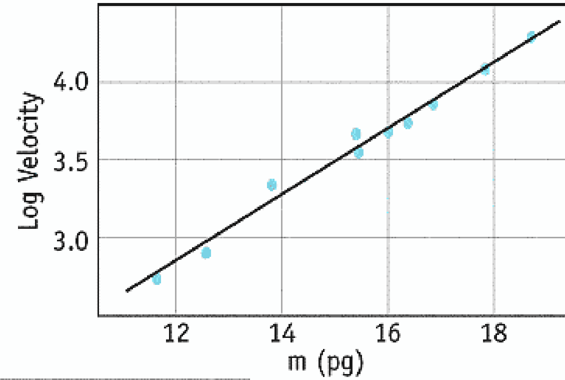
Plasma Epoch
Nuclei Form (180 seconds)
Protons and Neutrons Form (10-10 s)
Quarks Differentiate (10-34 s ?)

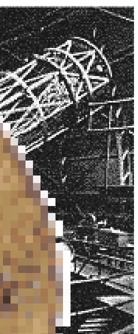
Inflation? $<10^{-38}$ seconds
Gravity waves produced

History of the Universe

The Big Bang

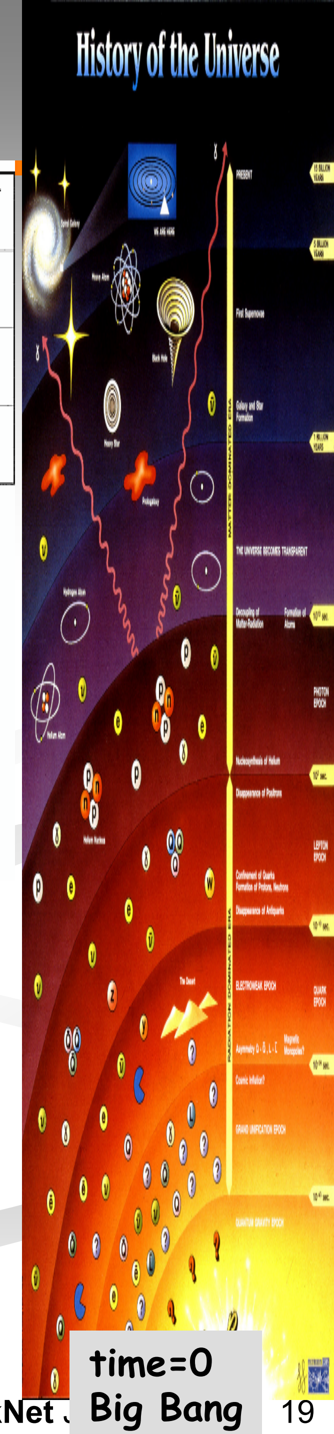






Mt. Wilson
100 Inch
Telescope

- In the 19 … an amazing thing- The un…
- If we allow ourselves to extrapolate this backwards, the universe must have started very small and dense.
- Indeed many theories predict the universe started as an infinitely small and dense *SINGULARITY* in space-time… the BIG Bang.



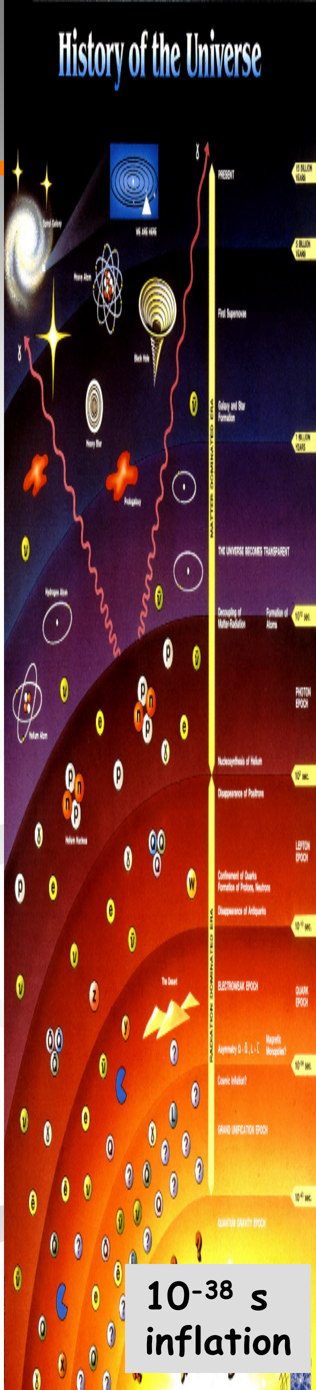
History of the Universe

Inflation

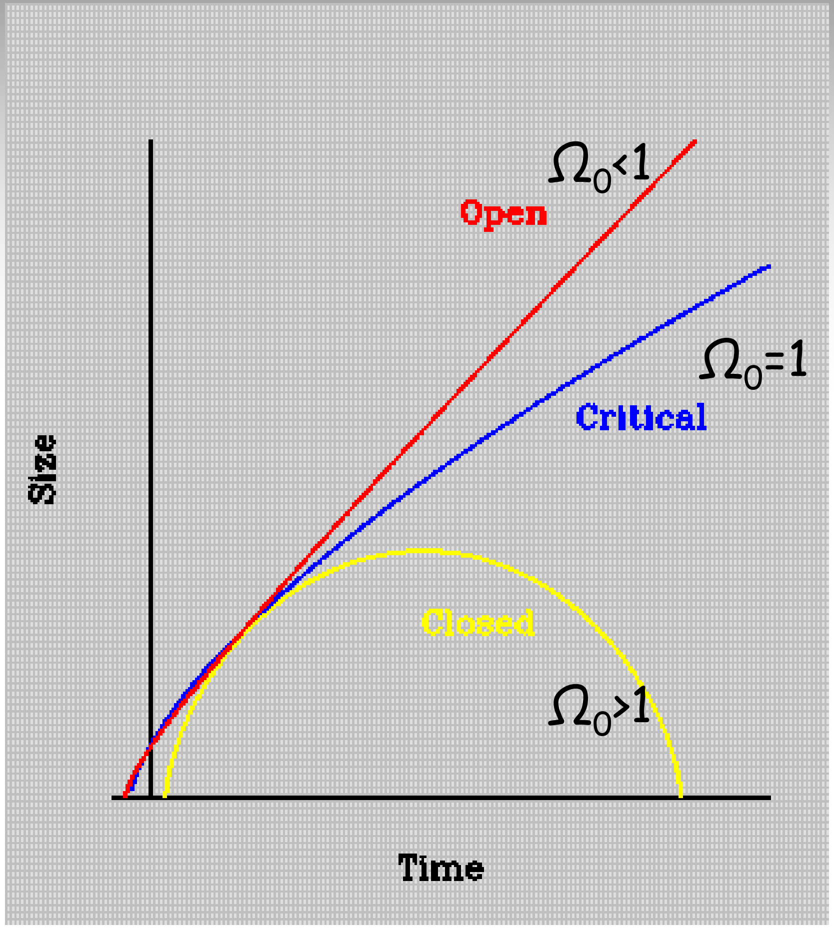
- at t~10^{-38} s ABB, the universe undergoes a phase transition causing an explosive 10^{30} exponential expansion
- leaves its imprint as ***inflationary gravity waves***

→ inflation provides answers for:

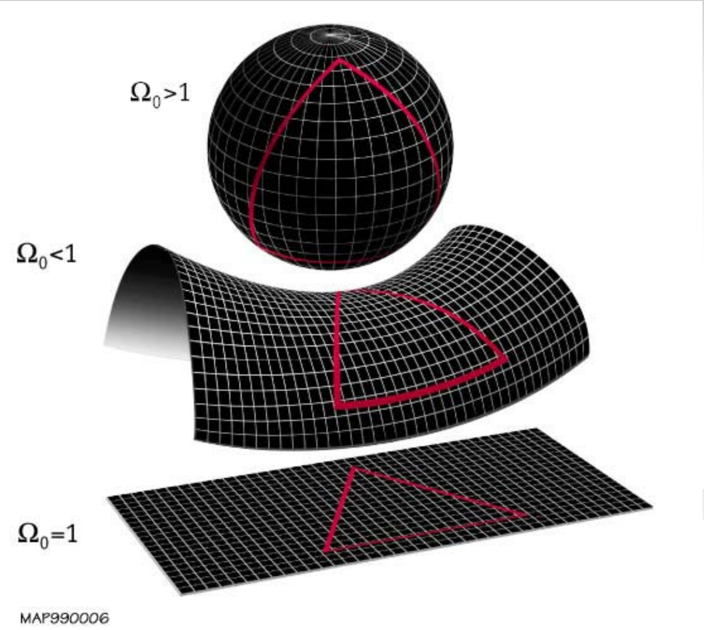
- horizon problem: explains why CMB is isotropic
- flatness problem (Ω=1): exponential expansion locally flattens spatial curvature to high precision.
- predicts (scale invariant adiabatic) density perturbations, which will eventually collapse under the pull of gravity to produce galaxies, stars,..

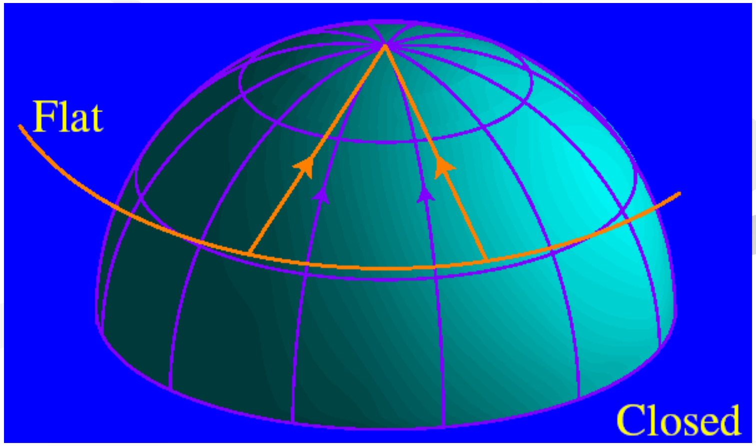


Curvature of Space-time



The density of the universe also determines its geometry.



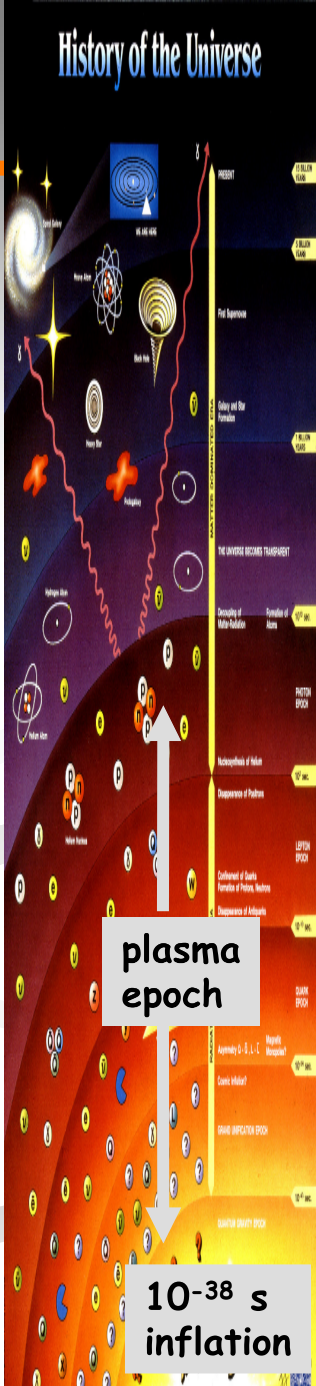


History of the Universe

Plasma Epoch, t <~ 400 000 years

- matter in the universe is charged- and hence opaque to light.
  - mean free path λ_C=2.5 Mpc (short!)

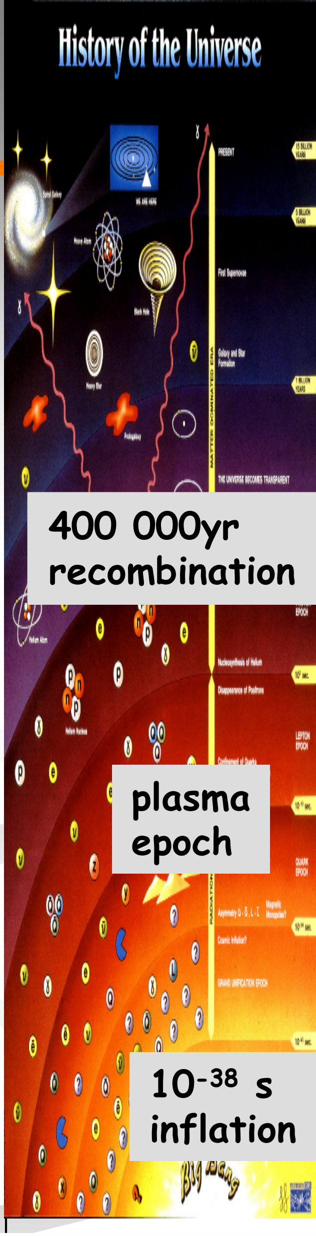
- matter and radiation are ***tightly coupled***
  - information about matter distributions are precisely encoded in radiation



History of the Universe

Recombination t~379 000 years ABB, T=3000K

- protons combined with electrons to form neutral hydrogen
  - recombination is sudden.
- this is the *"surface of last scattering"* for most photons- which travel unhindered to us, providing a snap-shot of the universe at time=379 000 years.

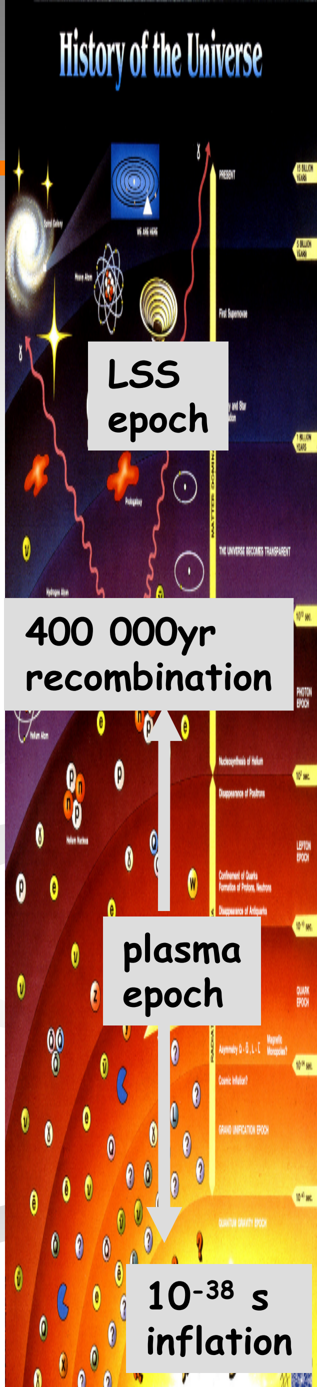


History of the Universe

Large Scale Structure Formation Epoch

- Matter collapses under gravity to form the rich structure (including us!) of the universe.
- photons are (almost!) unaffected
- Why the difference between Matter & Radiation now??
  - → *radiation pressure* resists the pull of gravity.
  - This is important, because it means that anything that happens to the photons between then and now is a small perturbation- and is easy to calculate.

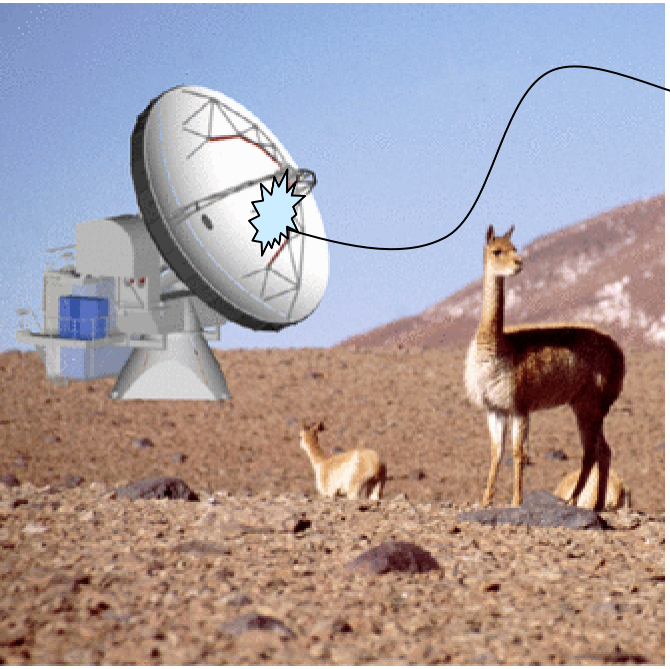
    So CMB evolution is ***theoretically easy (robust) to predict***.



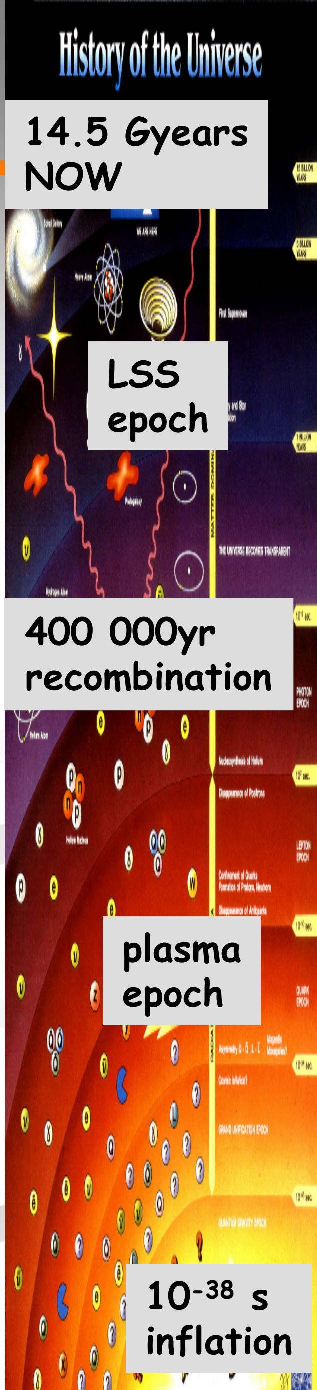
History of the Universe

NOW

- t~13 700 002 003 years ABB
- T=2.7 K (-270^0 C)



End of the line for a precious few of the photons, as we trap them in our detectors and glean a little information about the universe we live in.

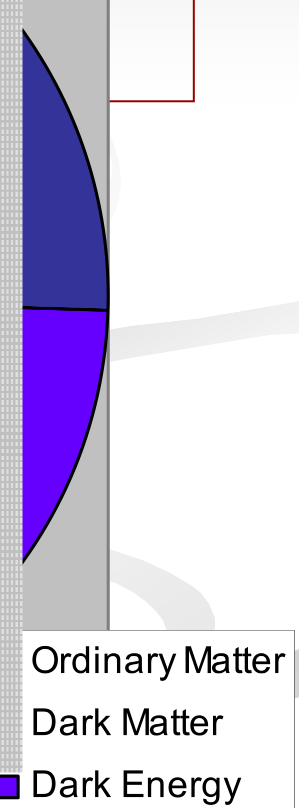


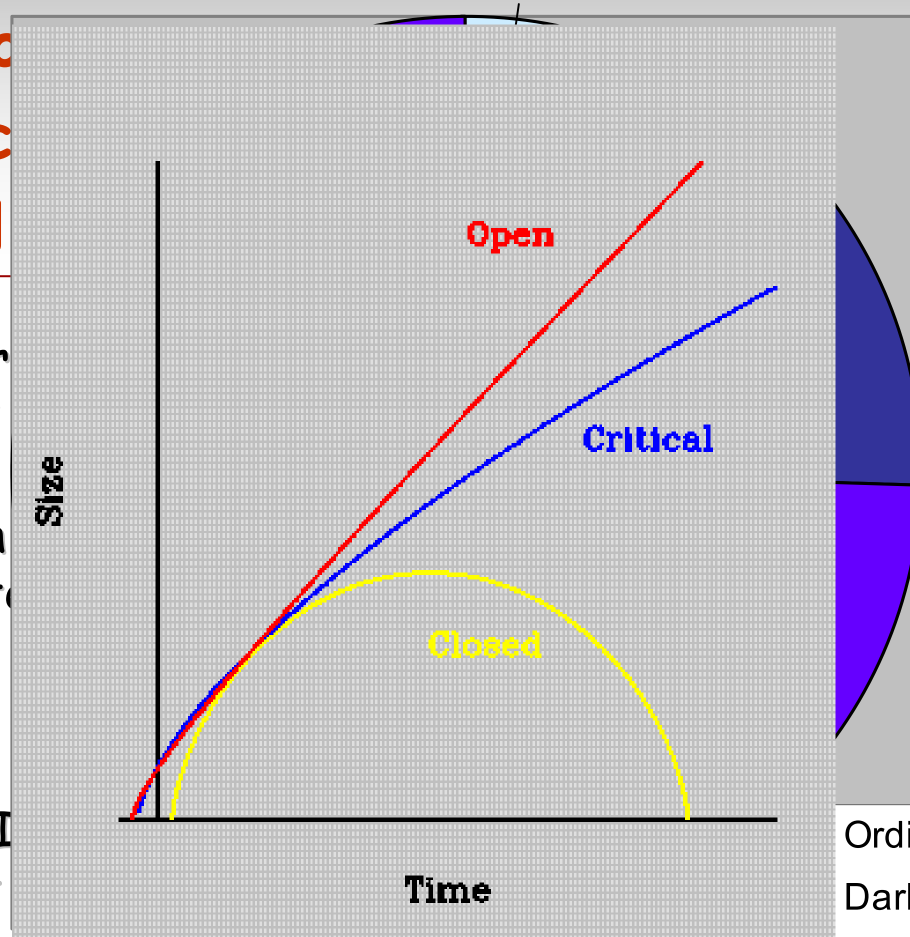
A new era for Cosmology

Part of the universe we "understand"

"my first reaction to ... se that grown people c ... h a schematic physical

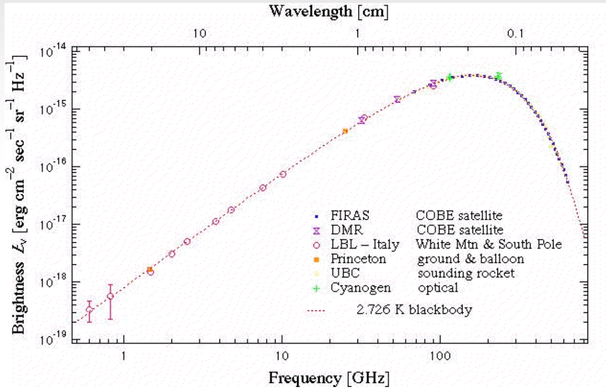
- Driven by precision measur... supernovae, Cosmology has
- The universe:
  - is SPATIALLY FLAT, with
  - consists primarily of myst... dark matter (22%) and dark energy (73%)
- The observations
  - are consistent with the BI... if the universe underwent INFLATION.





The Cosmic Microwave Background Radiation

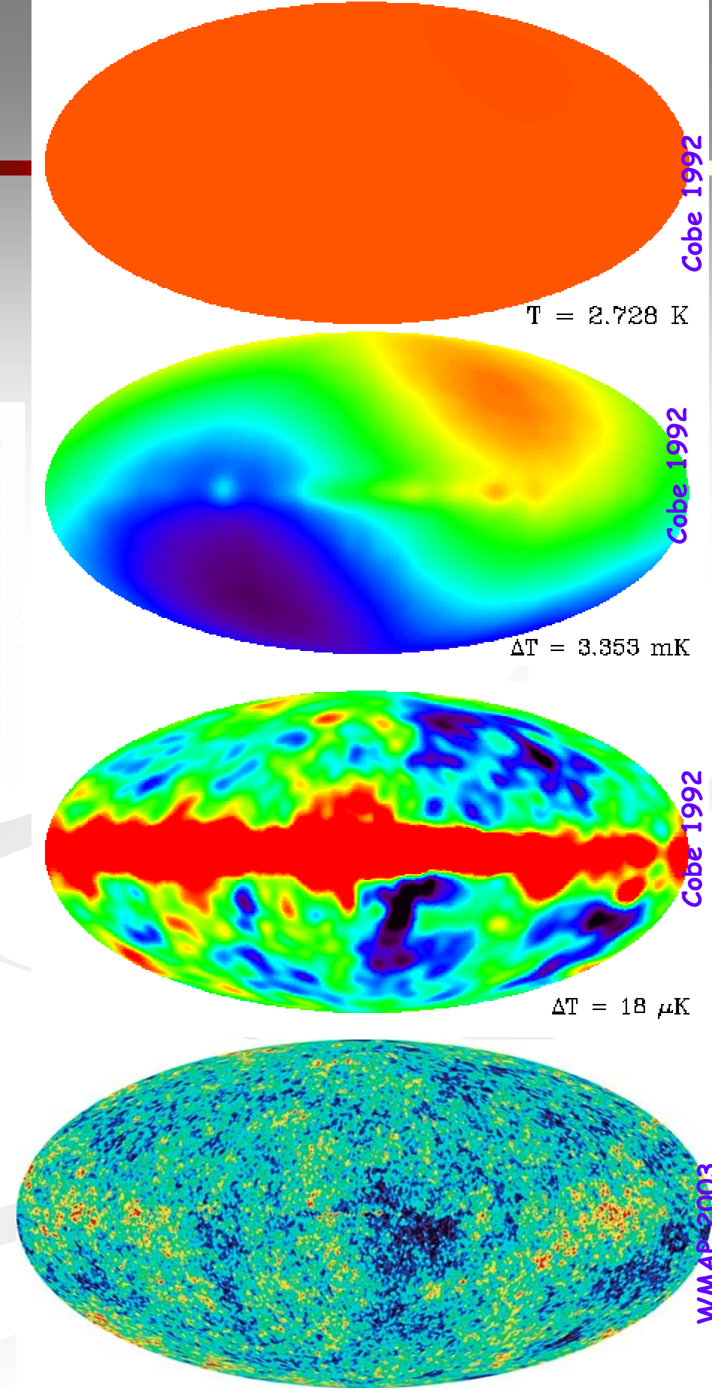
- CMB is a near perfect black body, 2.7° K



- Dipole Anisotropy 10^{-3}

  (our motion in the CMB `rest frame')

- Temperature Anisotropy 10^{-5}



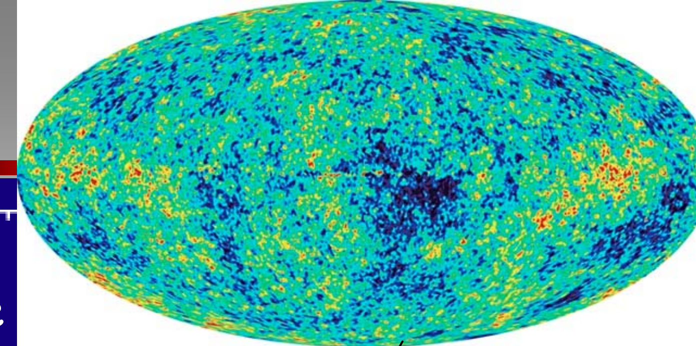
The Washington Post

New Findings Support Theory of 'Big Bang'

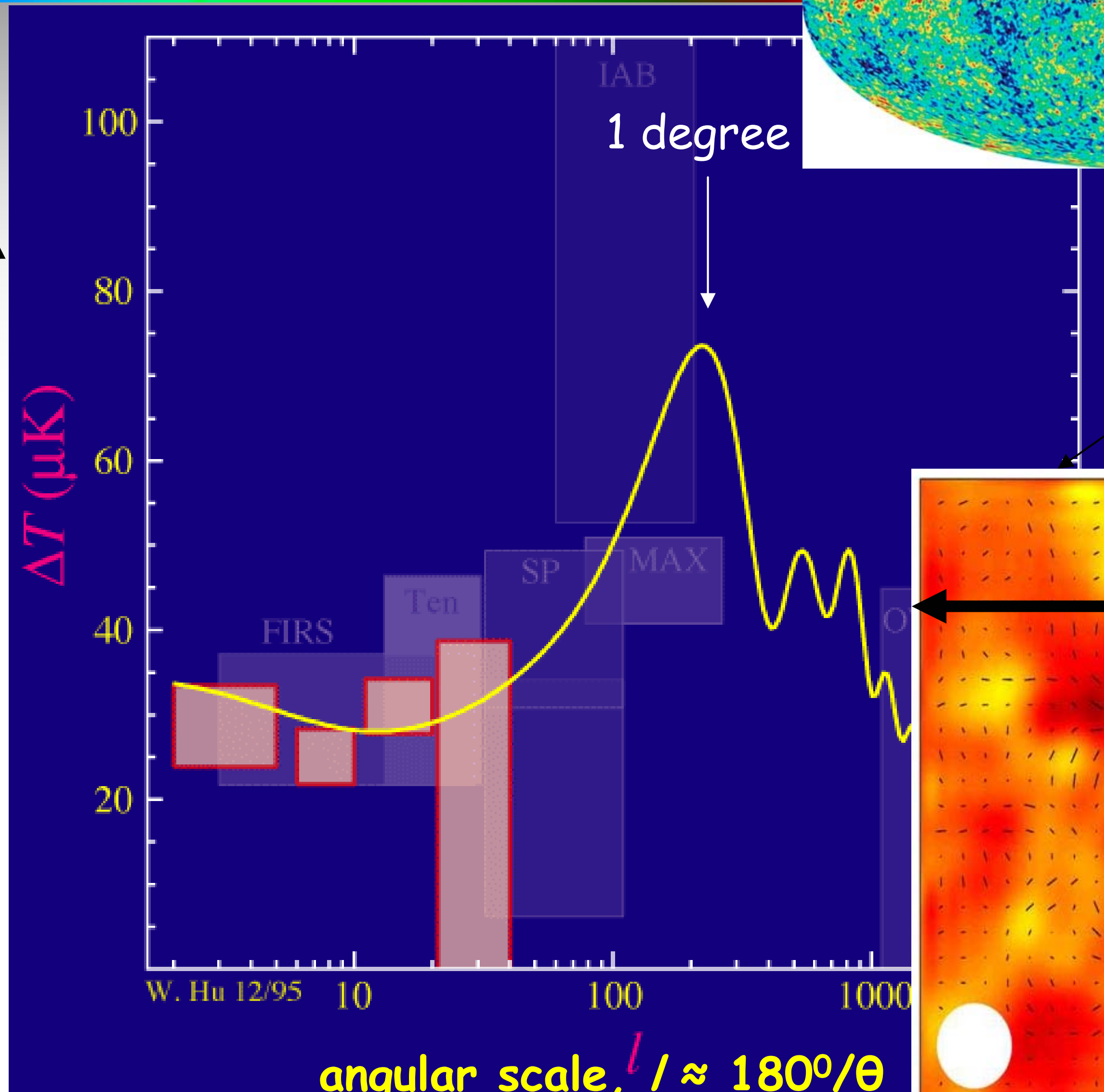
A team of scientists yesterday electrified the astronomical community by announcing the discovery of the largest and oldest cosmic

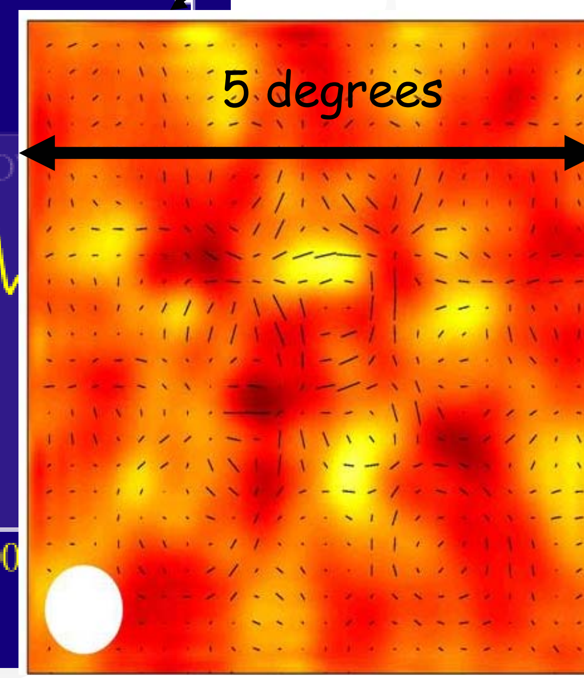
The COBE team made the first direct measurement of "ripples" born in the primeval explosion known as the "Big Bang" ...

The Power Spectrum



blotchy-ness
of the sky at a
particular scale

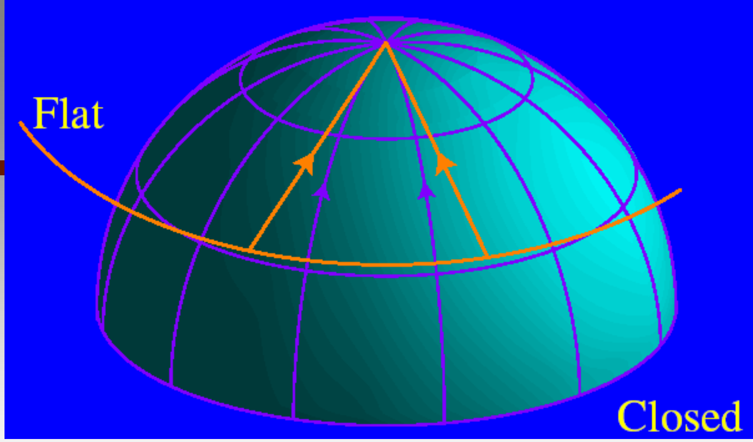


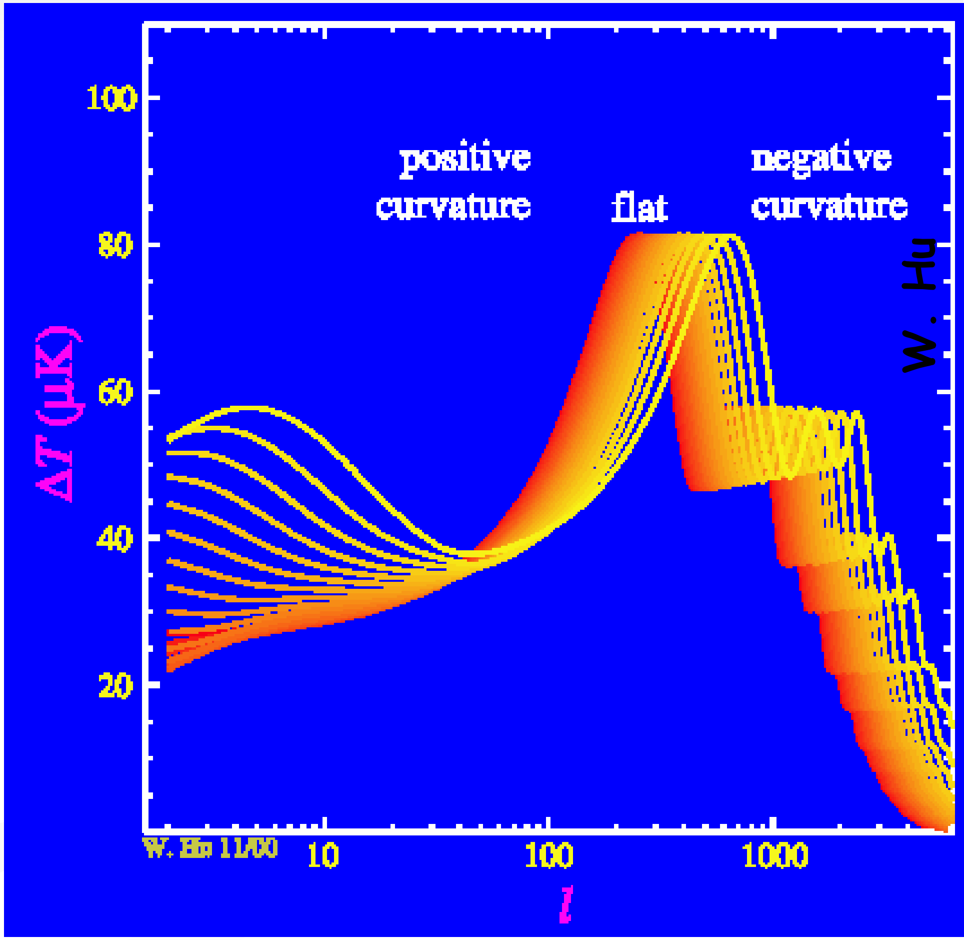


smaller scales

Curvature of Spacetime

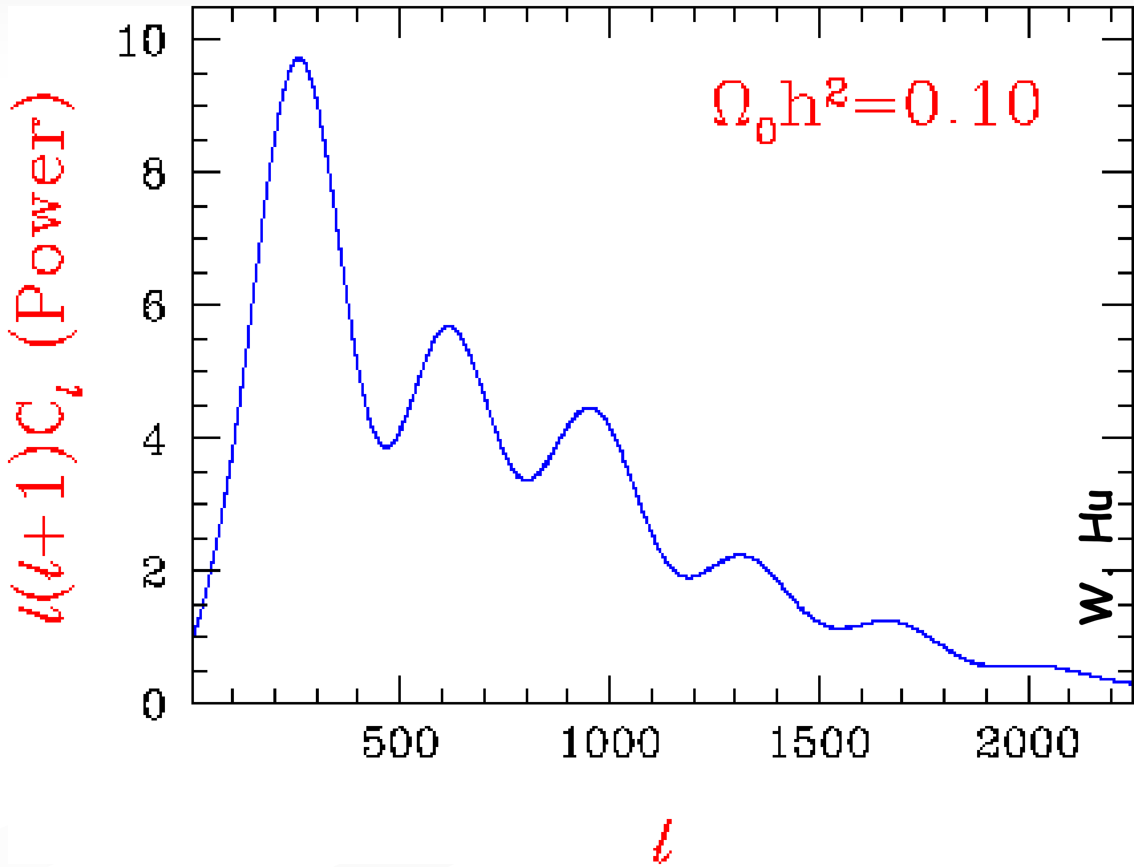
- The angular location of the first peak measures the curvature of spacetime, Ω_{tot}=1.
  - effectively measures if anisotropies travel straight out to us along curved paths.





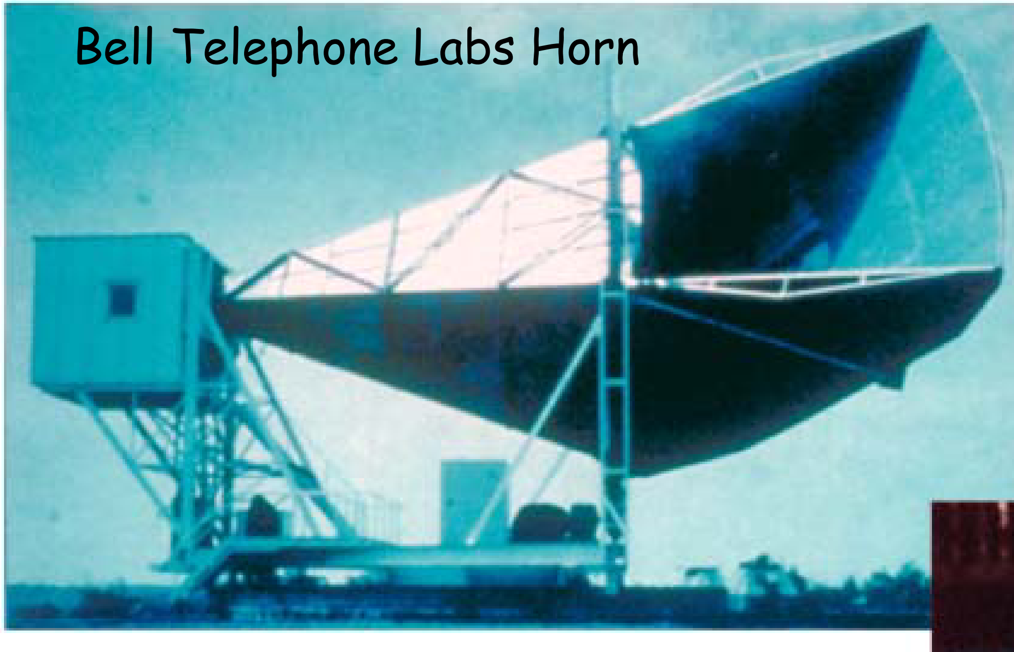
Power Spectrum: Ω_M

- the total amount of matter in the universe
  $\Omega_M = \Omega_b + \Omega_{CDM}$ determines the normalization of the power spectrum.

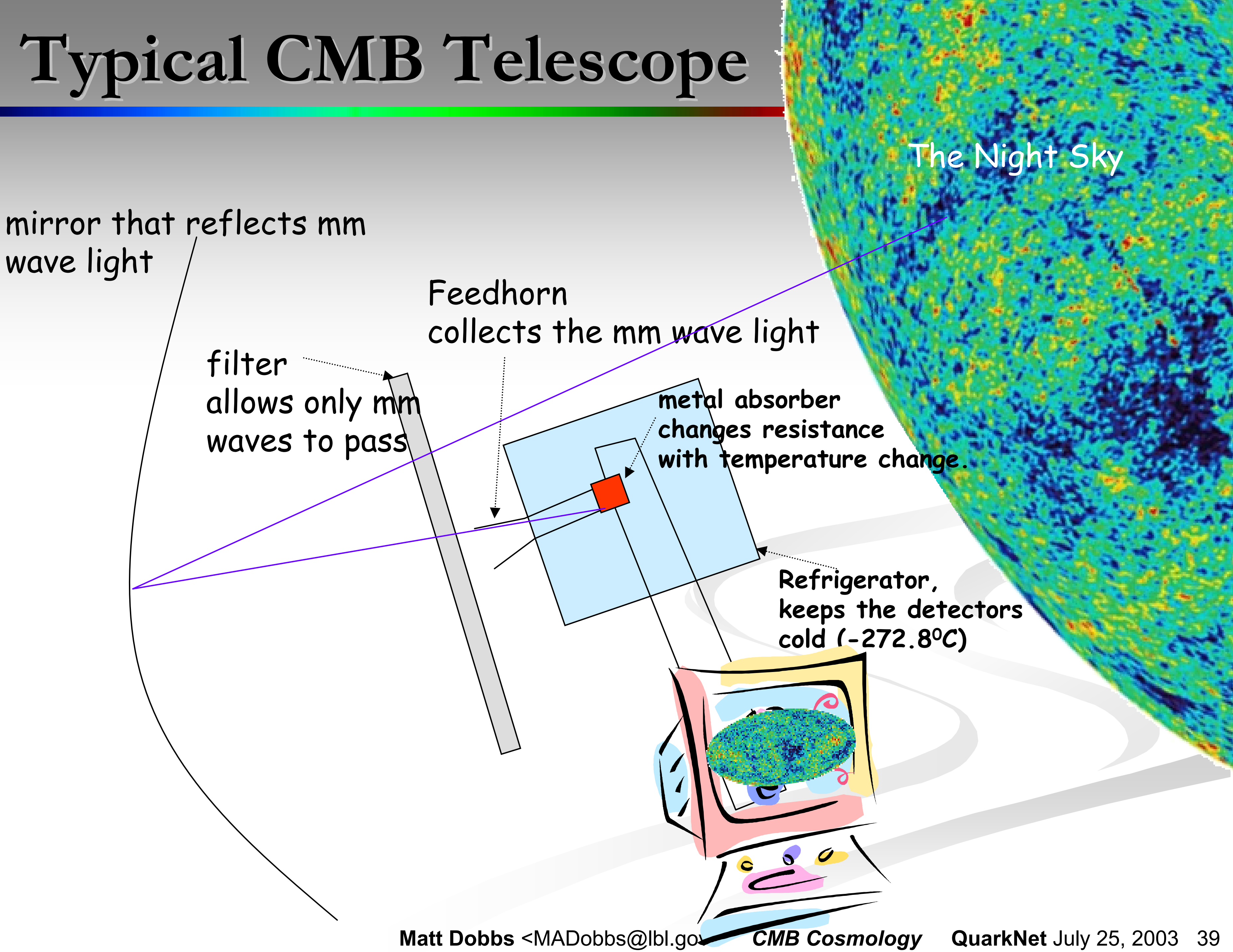


Measuring the CMB: 1. From the Ground

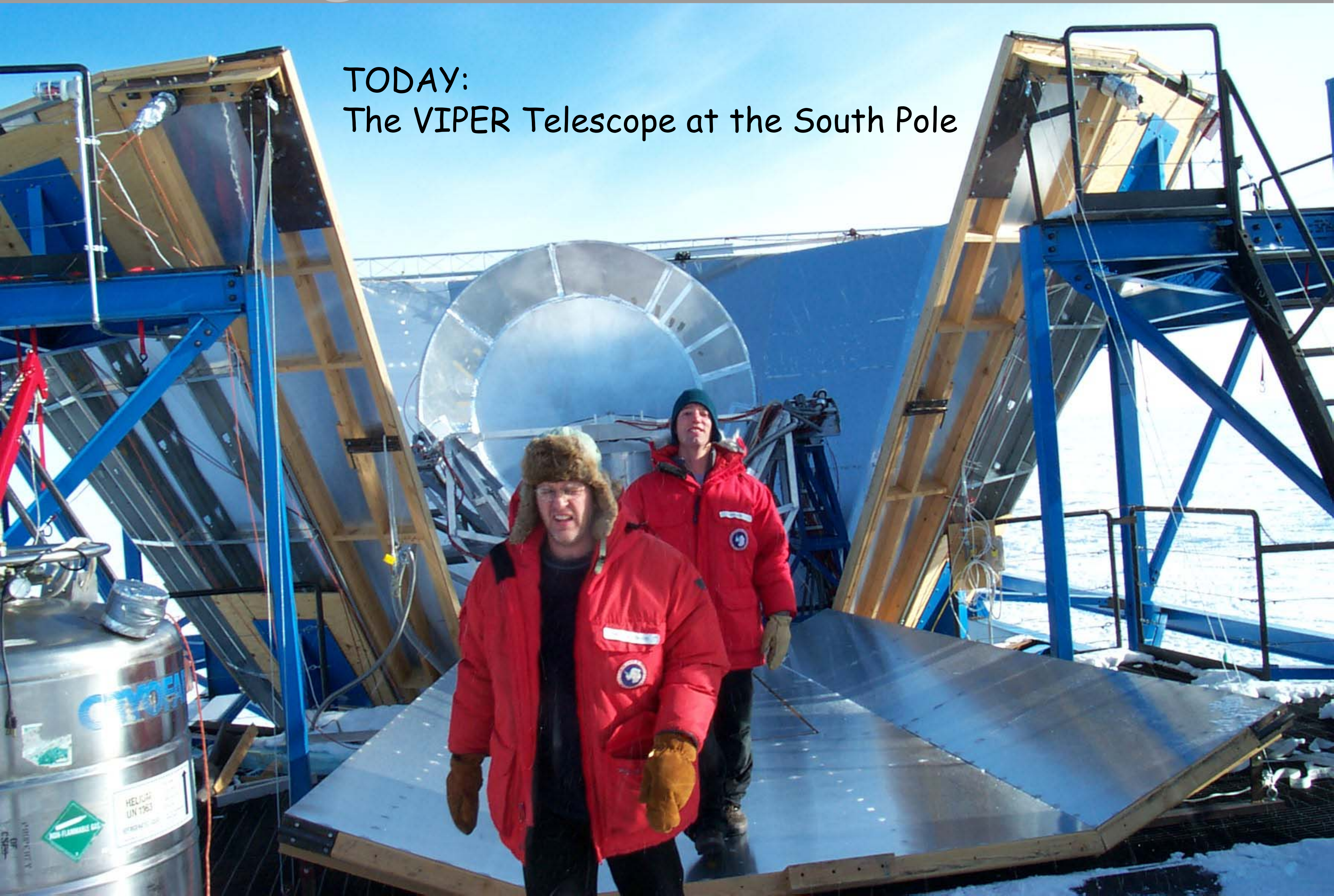
- Predicted (then forgotten) by Gamow, Alpher Herman in 1948, 1950.
- observed inadvertently in 1965 by Arno Penzias and Robert Wilson (1978 Nobel Prize)
- Dicke, Peebles, Roll, and Wilkinson gave the cosmological interpretation



Typical CMB Telescope



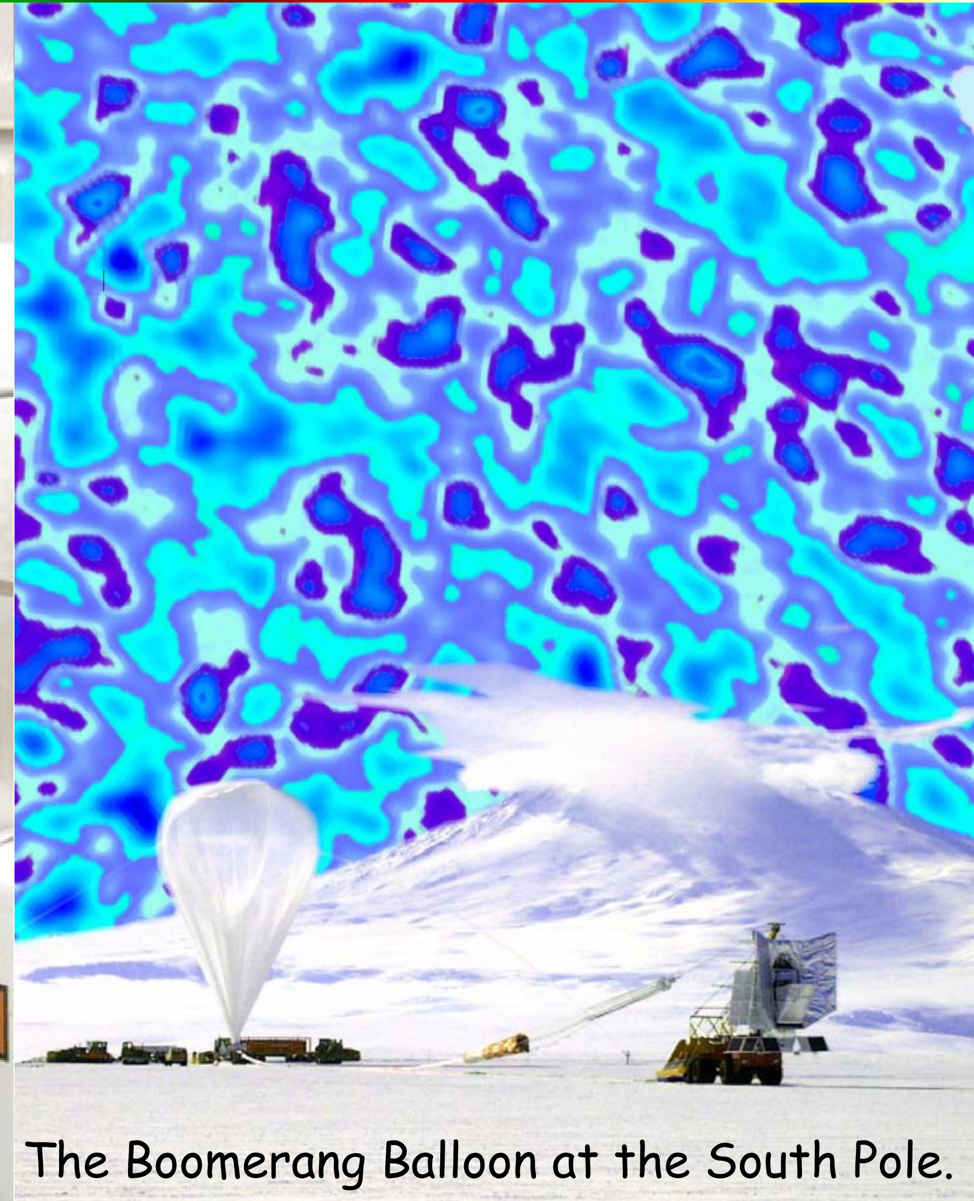
Measuring the CMB: 1. From the Ground



TODAY:
The VIPER Telescope at the South Pole

Measuring the CMB: 2. From Balloons

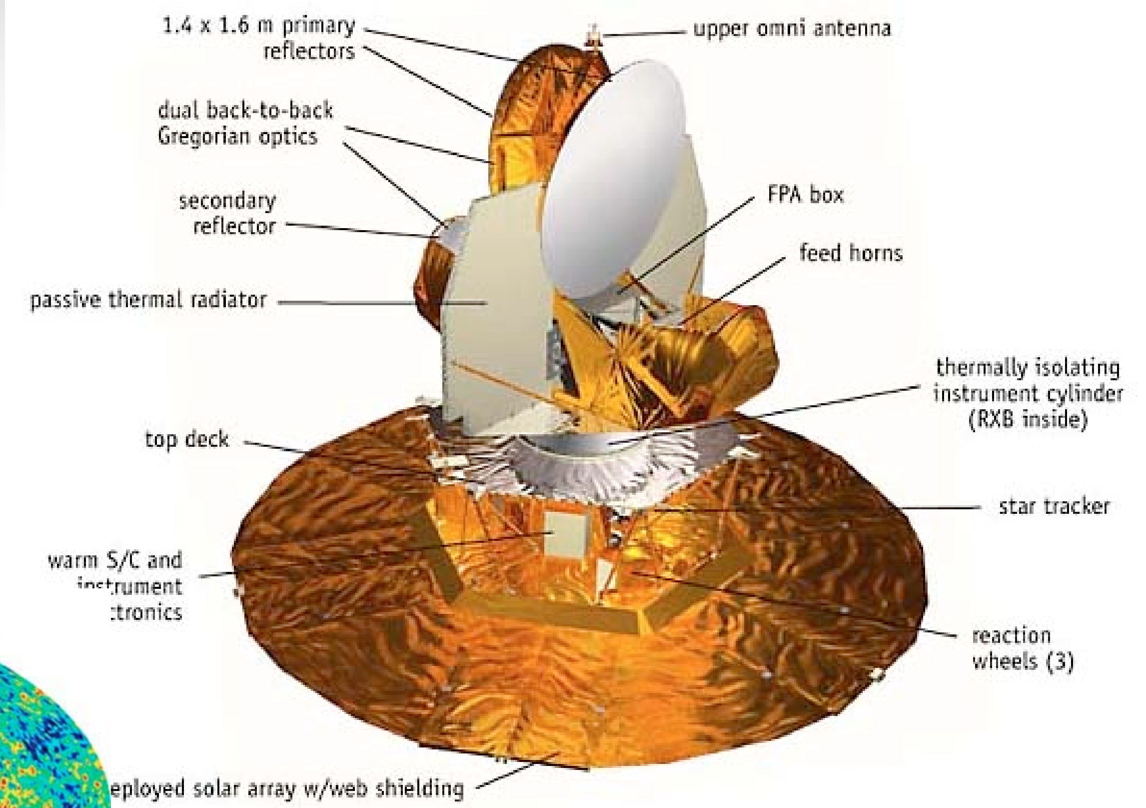
The Maxima Balloon Payload.

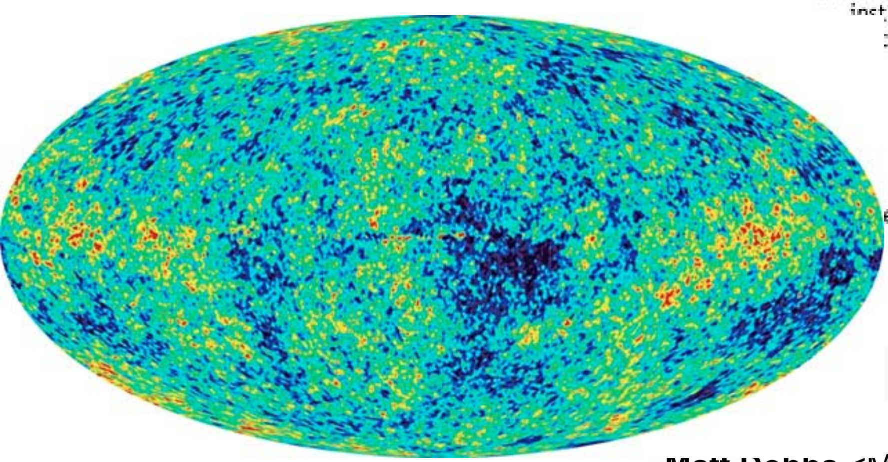


The Boomerang Balloon at the South Pole.

Measuring the CMB: 3. with Satellites

The Wilkinson Microwave Anisotropy Satellite was launched in June 2002, producing the most detailed MAP of the sky in the Microwave Band.

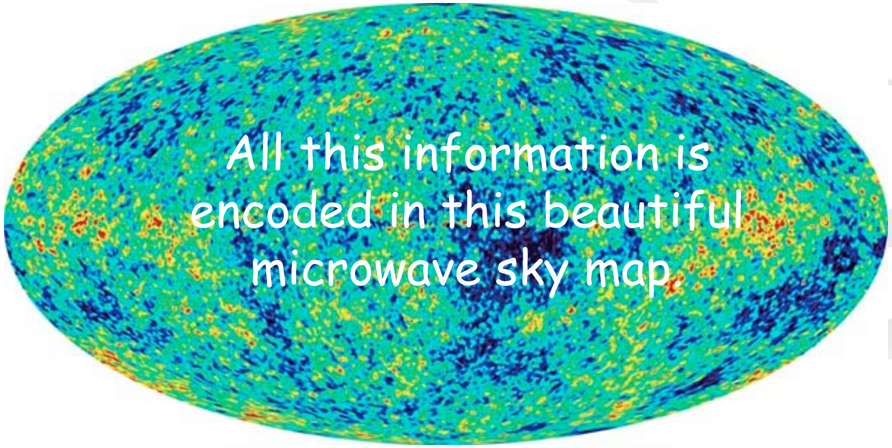




A further advantage of satellites is *full sky coverage.*

Measuring the CMB: 3. with Satellites

- Since QuarkNet 2002, the WMAP satellite data has been analysed:
  - The universe consists of about 4.44% baryons
  - which is included in the total matter inventory of 27%
    - most of the rest is mysterious cold dark matter.
  - expanding at 71 km/s /MPc.
  - age is 13.7$\pm$ 0.2 billion years
  - … and much more!



So far we've learned that:

- The CMB provides a snap-shot of the infant universe at the surface of last scattering
  - We've observed that the universe was homogenous and isotrophic then.
  - with tiny fluctuations that we believe collapsed into the brilliant Large Scale Structure we see today.
  - We've interpreted this information to infer the ingredients of the universe: matter, dark matter, radiation, etc.
  - and to measure the curvature of space time.

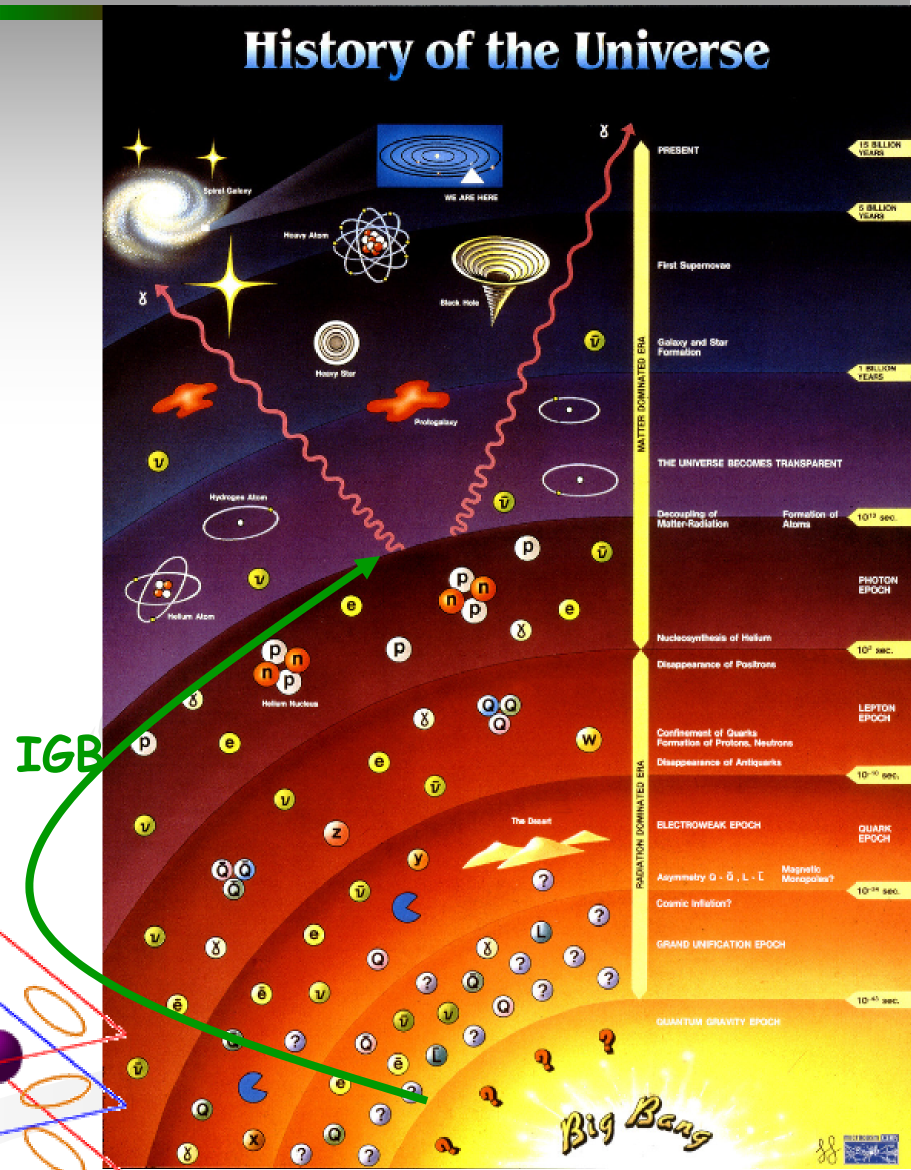
  → This is the best evidence we have for the big bang and inflation.
- What's next for CMB Science??

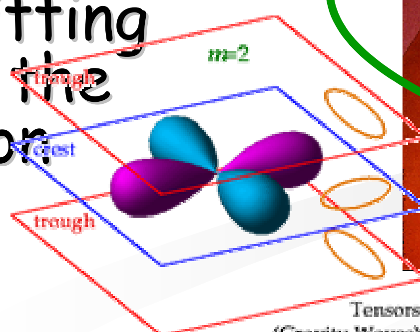
Advanced Topics

- Gravity Waves from Inflation
- Galaxy cluster searches using the CMB

Gravity Waves from Inflation

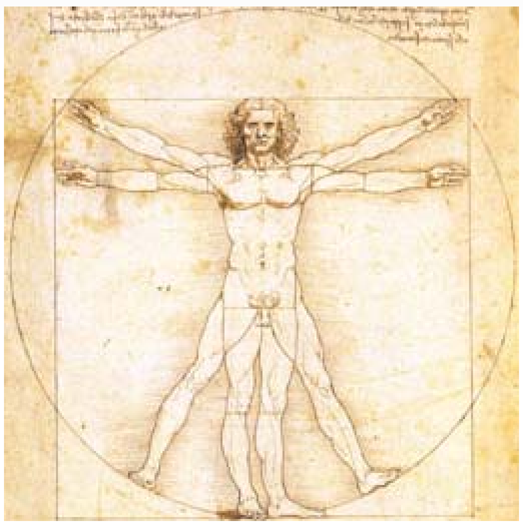
- Just as the CMB gives the fingerprint of the universe at the surface of last scattering,
- the fingerprint at the time of inflation (10^{-38}?, s) is encoded on the ***inflationary gravity wave background*** (IGB).
- This gravity wave fingerprint stretches and compresses spacetime on the surface of last scattering—transmitting that information to the CMB as a polarization signal.

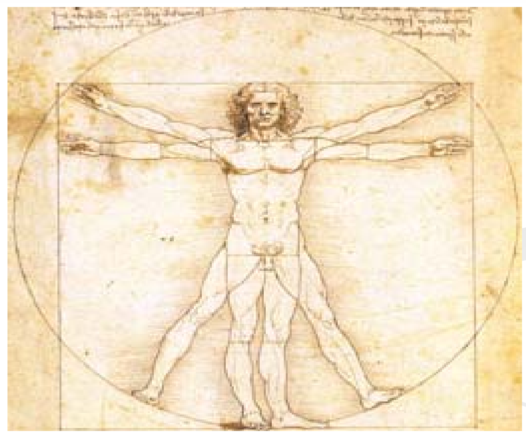


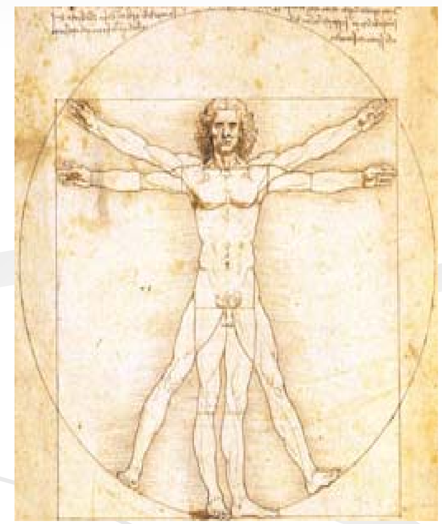


Gravity Waves from Inflation

- gravity waves stretch and compress space-time
- effectively stretching and compressing the wavelength of light along orthogonal directions



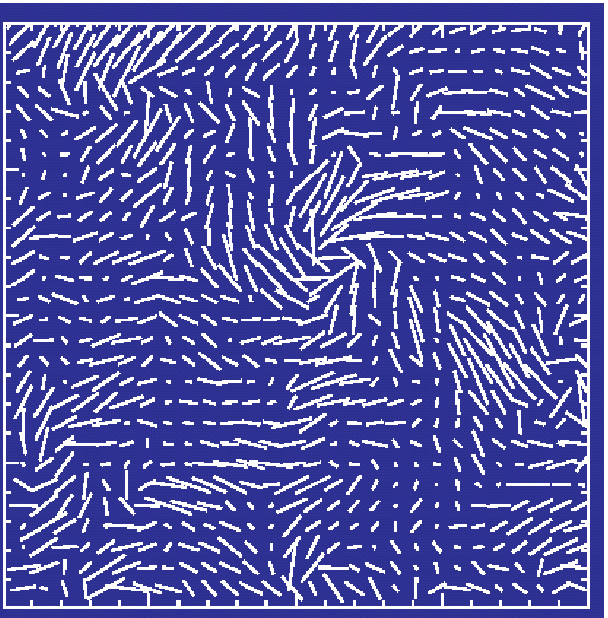




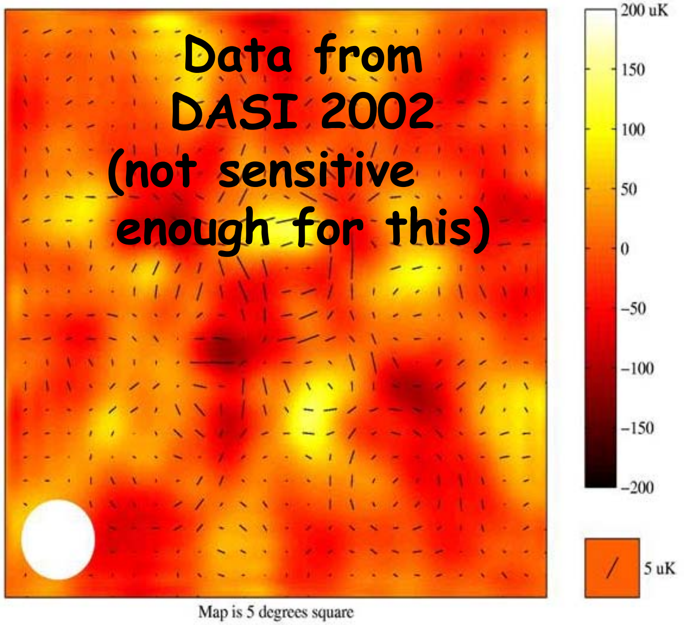
- This signature is frozen into the CMB at the surface of last scattering as a polarization.

Gravity Waves from Inflation

- By measuring the POLARIZATION of the CMB at every point on the sky, we can decode this signal.
  - (polarization is the spatial orientation of the light waves)
- the catch:
  - this polarization signal is 10^2 or many more times smaller than the temperature anisotropy.
    - we need really good detectors!



Example of what gravity waves would look like.



Gravity Waves from Inflation

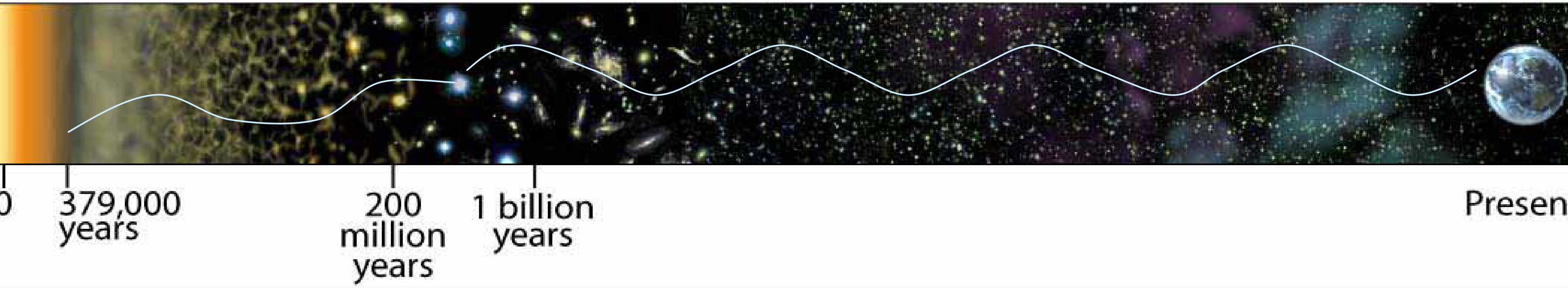
- Discovery of inflationary gravity waves would be ground breaking:
  - implies the existence of gravity waves (!!)
  - is the smoking gun of inflation– our best, and perhaps most provocative theory for the universe
  - would be the highest energy scale (10^{16} GeV) we've ever probed.

Galaxy cluster searches

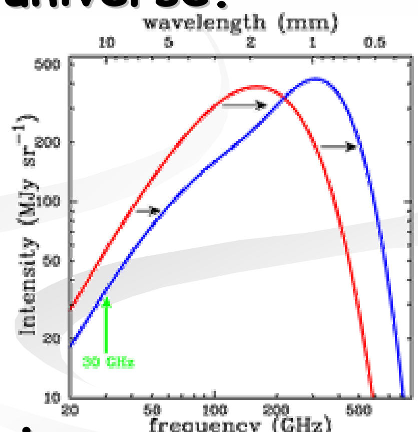
- Galaxy Clusters are the largest structured objects we know of.
- Usually we observe these clusters in the x-ray, optical, and other bands–
  - at great distances their signals fade away.
  - the furthest clusters are the youngest, and perhaps most interesting.
  - counting clusters as a function of distance (age!) gives us a lot of information about the evolution of the universe.

→ we'd like to observe and count clusters at great distances.

Galaxy cluster searches



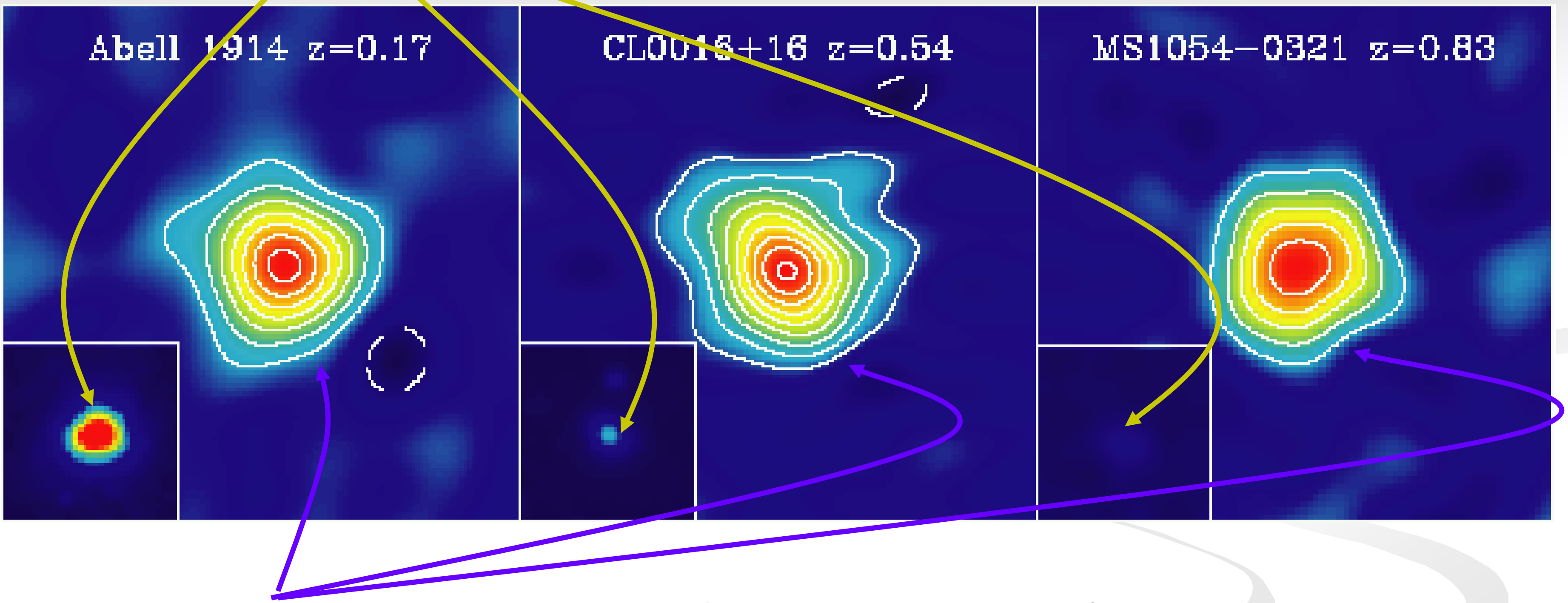
- CMB photons are used to backlight structure in the universe.
  - When CMB photons traverse galaxy clusters a few of them (1-2%) are kicked up to higher energies– the *Sunyaev Zeldovich Effect*.



  - By detecting these energy enhancements in the microwave sky-maps, we can observe distant galaxy clusters.
  - The clusters appear like "shadow puppets" with the CMB acting as a backlight.

Galaxy cluster searches

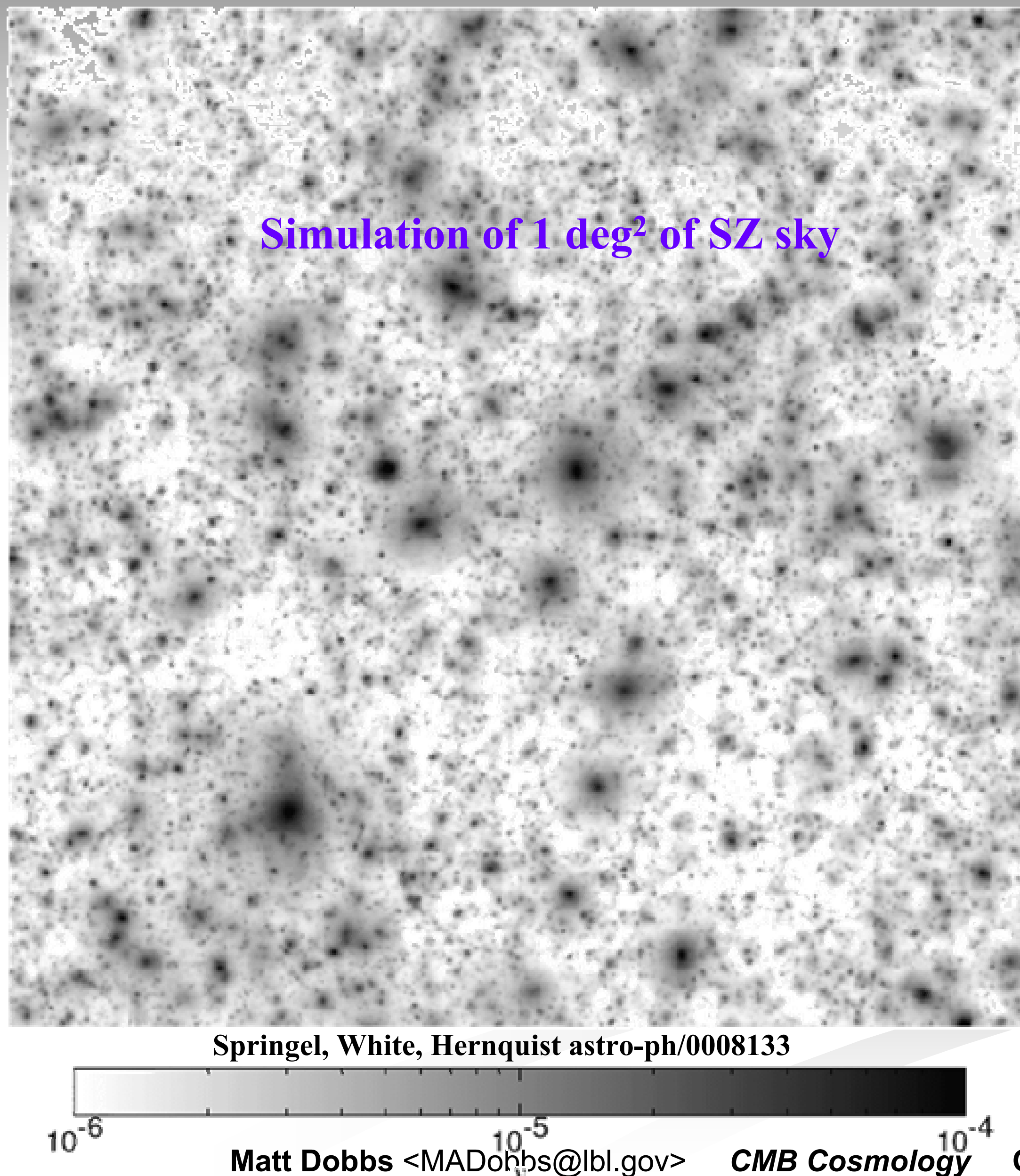
- In the X-ray sky, clusters fade away at high redshift.



- SZ observations do not fade away over large distances like x-ray or optical observations.

→ ***Clusters can be seen at any distance.***

Galaxy cluster searches

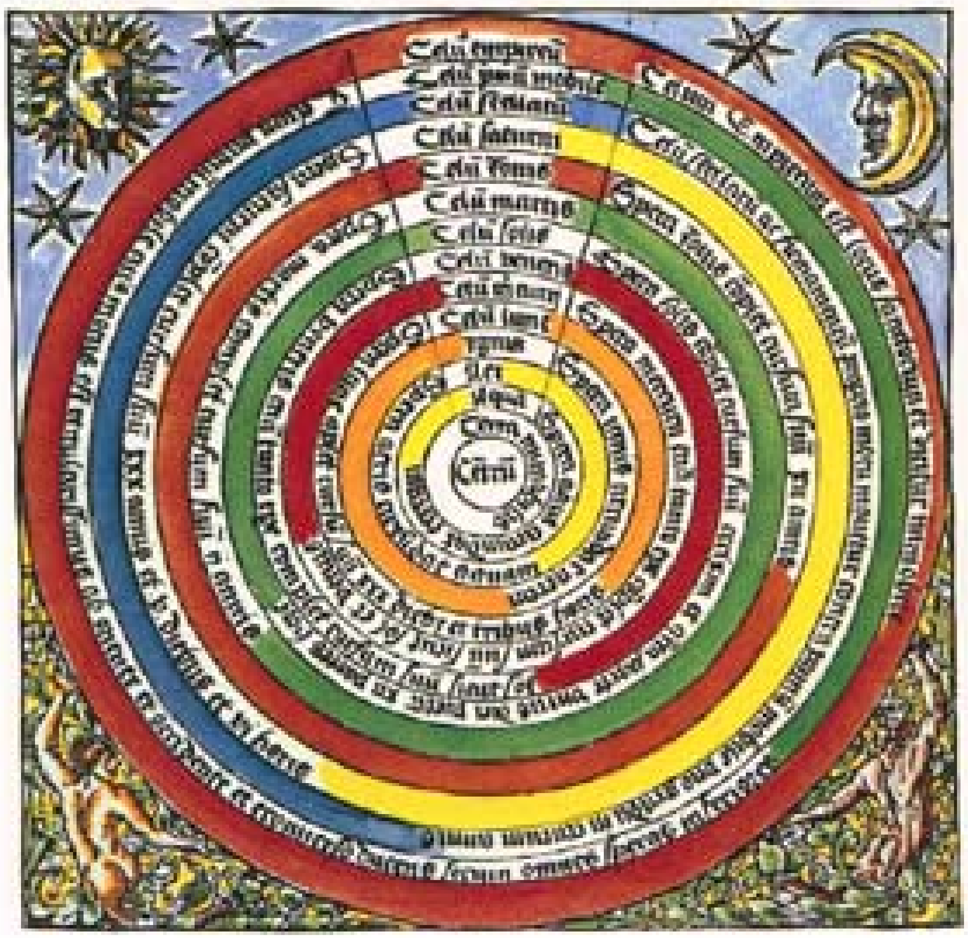


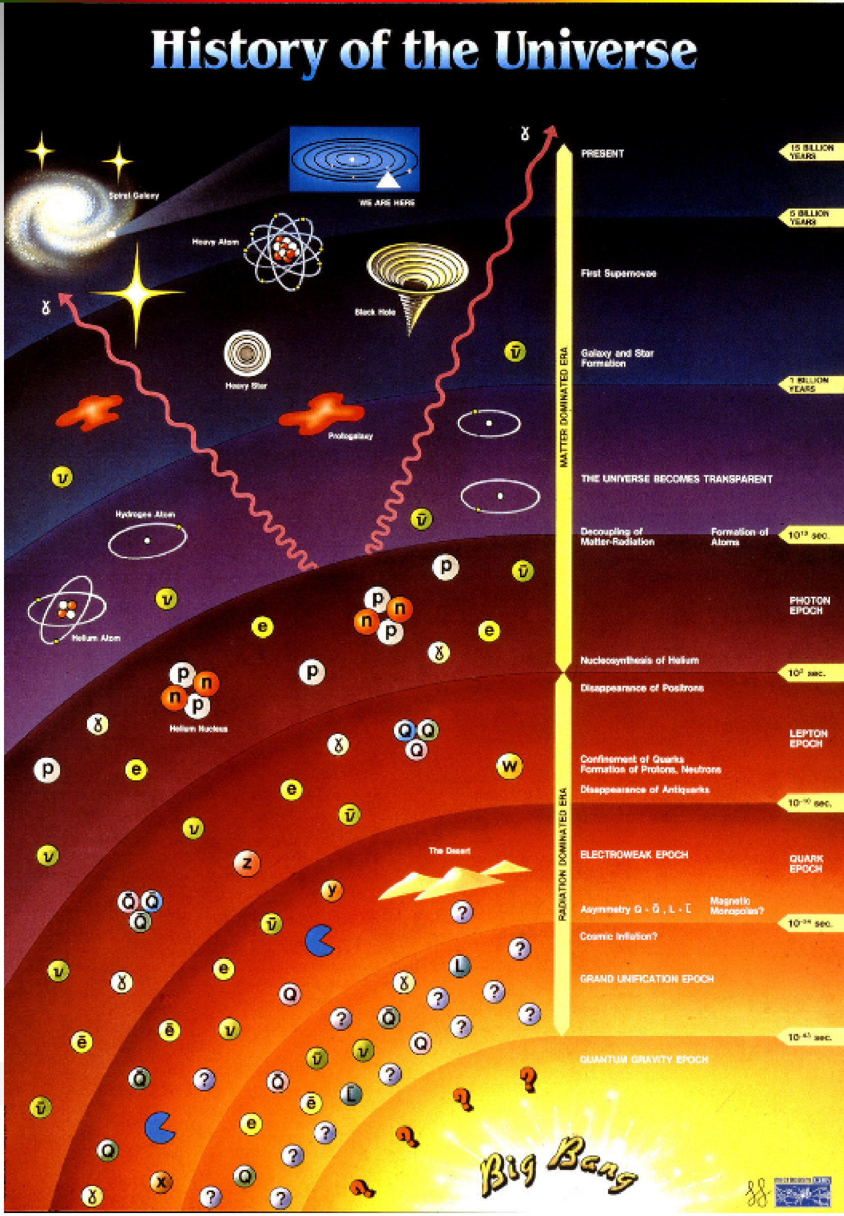
Springel, White, Hernquist astro-ph/0008133

Conclusions

- Cosmology is moving into a new era of precision measurements.
- The cosmic background radiation is a unique tool, providing us with the fingerprint of the universe as an infant (379 000 years ABB).
  - we measure it with special telescopes located on the ground, in balloons, and on satellites.
- Future prospects include:
  - looking back to 10^{-35} seconds ABB with the CMB polarization fingerprint of inflationary gravity waves
  - "x-raying" the universe for Galaxy Clusters with the SZ effect.

Aristotle's Scheme of the Universe





Resources

- The WMAP satellite teacher's resources page: http://map.gsfc.nasa.gov/m_or/tr_list.html
- Wayne Hu's Webpage, http://background.uchicago.edu/~whu/
- Alan Guth / Alan Lightman, "The Inflationary Universe: The Quest for a New Theory of Cosmic Origins"
- Brian Greene, "The Elegant Universe", 1998. (just a good read on Grand Unified Theories)